Chemical Evolution in the Large Magellanic Cloud

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ABSTRACT

We present a new input parameter set of the Pagel model for the LMC (Pagel & Tautvaišienė 1998) in order to reproduce the observations, including the star formation rate (SFR) history. It is concluded that high ratio of A (~ 0.17), which is the probability for 3-8$M_{\odot}$ stars to explode as SNe Ia, is required. As a result, a steep initial mass function (IMF) slope or existence of the outflow is not needed in order to attain the low [O/Fe] ratio in the LMC. As for the current supernova ratio, a high ratio (~ 1.3) is concluded by the new parameter set, which is consistent with the X-ray observations. Although we can not conclude that our solution is an unique one, we can conclude that no solution which can explain the observations as many as ours has been presented.

Subject headings: galaxies: chemical evolution — Magellanic Clouds — Large Magellanic Cloud — stars: abundances — supernovae: general

1. Introduction

Chemical evolution model for a galaxy is a tool from which we can infer the history of the galaxy. A chemical evolution model will be believed to be right if it can reproduce the observations about the galaxy, such as the age-metallicity relation, the present Fe distribution of stars, and the [O/Fe] versus [Fe/H] diagram. We can infer some important informations about the events in the galaxy, such as the inflow rate of the material and the chemical compositions of Type Ia/II supernovae using such a 'right' chemical evolution model. These informations give some constraints on other theories and numerical calculations. For example, people who are devoted to the formation of a galaxy or the nucleosynthesis in a supernova should take these constraints into consideration. If they can meet them, it means that their calculations are supported by the chemical evolution model. This is the reason why we try to construct a good chemical evolution model.

There are a lot of parameters in a chemical evolution model. We can not know *a priori* whether the number of the parameters is too much or too little. One concerned with a chemical evolution model should try to reduce the number of the free parameters in his model, while he should try to reproduce the observational data as many as possible. Unless such an effort, degenerate solutions that can explain some 'selected' observations will be reported one after another to the world. Even worse, if the history of the galaxy can not be determined uniquely using these solutions, we can not extract important informations about the events in the galaxy. This means that the aim of the chemical evolution model is not accomplished at all.

To put it concretely, we will consider the chemical evolution in the large magellanic cloud (LMC). There are some excellent works about it. For example, Tsujimoto et al (1995) and Pagel and Tautvaišienė (1998) reproduce the age-metallicity relation, the [O/Fe]-[Fe/H] diagram, and the present mass fraction of gas very well. However, some of the conclusions presented in Tsujimoto et al (1995) are incompatible with those in Pagel and Tautvaišienė (1998). The Tsujimoto model predicts (i) a steeper initial mass function (IMF) slope ($\sim$ 1.55 – 1.72) compared to that in our galaxy ($\sim$ 1.35; Salpeter 1955) and (ii) a higher relative frequency of Type Ia to Type II supernovae ($N_{\rm Ia}/N_{\rm II} \sim 0.2 - 0.25$) compared to that in our galaxy (0.15; Tsujimoto et al. 1995). On the other hand, the Pagel model does not need (i) a steeper IMF slope and does not predict (ii) a higher $N_{\rm Ia}/N_{\rm II}$ compared to those in our galaxy. Instead, (iii) they require data points to be shifted artificially upwards/downwards when they fit their model to the observations. The concluded histories of the star formation and the inflow rate of the material are also different between their models. This means that their solutions are the degenerate ones mentioned above. This situation is contrast to that for our galaxy. Their solutions for our galaxy resemble each other (Tsujimoto et al. 1995; Pagel & Tautvaišienė 1995).

It is true that we can not always obtain an unique solution even if we try to. Various solutions will be allowed when no strict constraint is derived from the observations. In fact, the number of the observations for the LMC is fewer than that for our galaxy. However, we think they do not make full use of the useful observational data for the LMC. For example, observations of the present Fe distribution of stars which will reflect the star formation rate (SFR) history are used to determine the parameters in the model of our galaxy (Tsujimoto et al. 1995; Pagel & Tautvaišienė 1995), while such observations are not used for the model of the LMC (Tsujimoto et al. 1995; Pagel & Tautvaišienė 1998). Even worse, their works contain trivial inconsistency in their analysis (see section 2.2). That is why we should obtain a solution for the LMC using the observations of the SFR and a consistent analysis before we conclude that the history of the LMC can not be determined uniquely by a chemical evolution model.

In this paper, we use the Pagel model and determine the values of the free parameters in his model by the observations of the LMC, including the observation of the SFR history (Olszewski 1993). We will discuss the meaning of the predictions derived from the model doing a consistent analysis. We can not conclude that our solution is an unique one, but we can conclude that no solution which can explain the observations as many as ours has been presented. In section 2, formulation of the Pagel model is explained. Results are shown in section 3. Discussion and summary are presented in section 4 and 5.

2. Formulations

2.1. The Pagel Model

In this subsection, we present the formulation of the Pagel model. We consider one zone and assume that the gas is distributed uniformly and the heavy elements are well-mixed within the zone. Once we make such an assumption, any physical quantum is determined uniquely as a function of time in the model. This means that we do not try to reproduce a dispersion of the observations from the beginning. The aim of such a model is to reproduce the averaged value of the observations. If it can not, it will lose its justification for existence.

They introduced a dimensionless time-like variable u, defined by

$$u \equiv \int_0^t \omega(t')dt' \tag{1}$$

where $\omega(t)$ is the transition probability for diffuse material ('gas') to change into stars in unit time at time t. This means the simple linear star formation law

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \omega g \quad \text{or} \quad \frac{\mathrm{d}s}{\mathrm{d}u} = g \tag{2}$$

where $s(u) = \alpha S(u)$ is the mass in the form of long-lived stars (including compact remnants), and S is the mass of all stars that were ever born up to time t. α is the lock-up fraction (assumed constant). The fate of a star is divided into three classes; a long-lived star, Type Ia supernova, and Type II supernova. The ratio of their occurrence possibility is assumed to be α:α_1:1-α-α_1. $g(u)$ is the mass of gas in the system under consideration.

The evolution of the total baryon mass of the system is given by

$$\frac{\mathrm{d}}{\mathrm{d}t}(s+g) = f(t) + e(t) \tag{3}$$

where $f(t)$ and $e(t)$ are the inflow and outflow rates of the material, respectively. Inflow is assumed to occur at a rate

$$f(t) = \omega(t)\mathrm{e}^{-u}. \tag{4}$$

The inflowing material is assumed to be unprocessed. On the other hand, outflow is assumed to occur at a rate

$$e(t) = \eta\frac{\mathrm{d}s}{\mathrm{d}t} = \eta\omega g. \tag{5}$$

η is a free parameter.

We explain the evolution of the metallicity. The mass fraction of ith element in the gas, Z_i, is divided into two terms. One is the term for the instantaneous recycling, $Z_{1,i}$, and the other is the term for the delayed production, $Z_{2,i}$. Type II/Ia supernovae contribute to the evolution of $Z_{1,i}$ and $Z_{2,i}$, respectively. The life-time of Type II supernova is much shorter ($\sim$ several Myrs) than the age of the LMC ($\sim$ 15 Gyrs). So Type II supernovae can be treated to explode when their progenitors are born in a chemical evolution model. This is the meaning of the instantaneous recycling. On the other hand, the life-time of Type Ia supernovae (few Gyrs) is comparable to the age of the LMC. So their life-time is taken into consideration in a chemical evolution model. This is the meaning of the delayed production.

The evolution of $Z_{1,i}$ obeys the following equation:

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}(gZ_{1,i}) &= \frac{\mathrm{d}S}{\mathrm{d}t}(1-\alpha-\alpha_1)x_i - \frac{\mathrm{d}S}{\mathrm{d}t}\alpha Z_{1,i} \qquad \left(x_i = \frac{m_{i,\mathrm{II}}}{M_{\mathrm{II}}}\right) \\ &= \frac{\mathrm{d}s}{\mathrm{d}t}\frac{1-\alpha-\alpha_1}{\alpha}x_i - \frac{\mathrm{d}s}{\mathrm{d}t}Z_{1,i} \\ &= \omega g P_{1,i} - \omega g Z_{1,i}\end{aligned} \tag{6}$$

where $m_{i,\mathrm{II}}$ and M_{II} are averaged mass of ith heavy element and total mass of Type II supernova. $m_{i,\mathrm{II}}$ is defined as

$$m_{i,\mathrm{II}} = \frac{\int_{m_l}^{m_u} m_{i,\mathrm{II}}(m)\phi(m)m^{-1}\mathrm{d}m}{\int_{m_l}^{m_u} \phi(m)m^{-1}\mathrm{d}m} \quad \text{with} \quad \phi(m) = m^{-x}. \tag{7}$$

$m_{i,\mathrm{II}}(m)$ is the ith heavy-element mass produced in a star of main-sequence mass m. $\phi(m)$ is the initial mass function (IMF) and x is the slope of the IMF. The bounds for SNe II progenitors were taken to be $m_l = 10M_\odot$ and $m_u = 50M_\odot$, respectively (Tsujimoto et al. 1995). M_{II} is defined as

$$M_{\mathrm{II}} = \frac{\int_{m_l}^{m_u} \phi(m)\mathrm{d}m}{\int_{m_l}^{m_u} \phi(m)m^{-1}\mathrm{d}m}. \tag{8}$$

The evolution of $Z_{2,i}$ is given by

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}(gZ_{2,i}) &= \frac{\mathrm{d}S(t-t_{\mathrm{Ia}})}{\mathrm{d}t}\alpha_1 y_i - \frac{\mathrm{d}S}{\mathrm{d}t}\alpha Z_{2,i} \qquad \left(y_i = \frac{m_{i,\mathrm{Ia}}}{M_{\mathrm{Ia}}}\right) \\ &= \frac{\mathrm{d}s(t-t_{\mathrm{Ia}})}{\mathrm{d}t}\frac{\alpha_1}{\alpha}y_i - \frac{\mathrm{d}s}{\mathrm{d}t}Z_{2,i} \\ &= \omega(t-t_{\mathrm{Ia}})g(t-t_{\mathrm{Ia}})P_{2,i} - \frac{\mathrm{d}s}{\mathrm{d}t}Z_{2,i}\end{aligned} \tag{9}$$

where t_{Ia} is the averaged lifetime of SNe Ia progenitors.

In their formulation, the frequency of SNe Ia ever occurred relative to SNe II is obtained as

$$\frac{N_{\mathrm{Ia}}}{N_{\mathrm{II}}} = \frac{P_{2,i}}{P_{1,i}}\frac{m_{i,\mathrm{II}}}{m_{i,\mathrm{Ia}}}\frac{s(u_{\mathrm{now}}-\omega t_{\mathrm{Ia}})}{s(u_{\mathrm{now}})} \tag{10}$$

where $u_{\rm now}$ is the present value for u. When we ignore the lifetime of supernova progenitors, $N_{\rm Ia}/N_{\rm II}$ is also written as

$$\frac{N_{\rm Ia}}{N_{\rm II}} = \frac{A\int_{3M_\odot}^{8M_\odot} m^{-(1+x)}}{\int_{10M_\odot}^{50M_\odot} m^{-(1+x)}}, \tag{11}$$

where A is the probability for (3-8)$M_\odot$ stars to explode as SNe Ia (Tsujimoto et al. 1995). So, we can estimate the value of A when $N_{\rm Ia}/N_{\rm II}$ and x are determined from a chemical evolution model.

As for the current supernova rates, we can calculate from Eq. (2) and (10) as

$$\frac{\dot{N}_{\rm Ia}}{\dot{N}_{\rm II}} = \frac{P_{2,i}}{P_{1,i}}\frac{m_{i,\rm II}}{m_{i,\rm Ia}}\frac{\omega(t-t_{\rm Ia}){\rm g}(t-t_{\rm Ia})}{\omega g}. \tag{12}$$

2.2. Extension of the Pagel Model

In this subsection, we explain the extension of the Pagel model in this study. At first, the problems with $P_{1,i}$ and $P_{2,i}$ are explained. As is clear from Eq. (6) and (9), $P_{1,i}$ and $P_{2,i}$ are proportional to $m_{i,\rm II}$ and $m_{i,\rm Ia}$, respectively. To put it concretely, $P_{1,\rm Fe}$, $P_{1,\rm O}$, $P_{2,\rm Fe}$, and $P_{2,\rm O}$ meet the relation

$$\frac{P_{1,\rm O}}{P_{1,\rm Fe}} = \frac{m_{\rm O,II}}{m_{\rm Fe,II}} \quad \text{and} \quad \frac{P_{2,\rm O}}{P_{2,\rm Fe}} = \frac{m_{\rm O,Ia}}{m_{\rm Fe,Ia}}. \tag{13}$$

When one regards all of $P_{1,i}$ and $P_{2,i}$ to be free parameters like Pagel and Tautvaišienė (1998), it means he does not believe the results of the calculation of supernova nucleosynthesis. Of course, such a standpoint is one of the natural ones. However, he can not use Eq. (10) and Eq. (12) because results of supernova nucleosynthesis are used in these equations. In this study, we use the results of the calculation of supernova nucleosynthesis and use Eq. (10) and Eq. (12) in order to estimate the occurrence frequency of SNe Ia relative to SNe II. We use the results of calculations for SNe Ia (Nomoto et al. 1984). So the ratio $P_{2,\mathrm{O}}/P_{2,\mathrm{Fe}}$ is fixed from the beginning. As for $P_{1,\mathrm{i}}$, we give the values for $P_{1,\mathrm{Fe}}$ and $P_{1,\mathrm{O}}$ so as to fit the model to the observations. Then the IMF slope is determined from Eq. (7) and A is determined from Eq. (10) and Eq. (11) using the results of calculations for SNe II (Hashimoto 1995).

Next, we explain what observations are used in order to check the validity of the model. Pagel and Tautvaišienė (1998) used the age-metallicity relation, the present mass fraction of the gas, and the [α/Fe] versus [Fe/H] diagram. α represents α-nuclei, such as O, Si, S, and Ca. [α/Fe] versus [Fe/H] diagram is used to extract the contribution of SNe II because α-nuclei, especially oxygen, are synthesized mainly in SNe II. In this study, the [O/Fe] versus [Fe/H] diagram is used because we will be able to extract SNe II's contribution best by using the observations of oxygen. To check the dependence of the results on the α-nuclei to be used in this analysis means to check the validity of the calculation of the supernova nucleosynthesis itself. This problem will be discussed in the forthcoming paper.

In this study, we also add two observational facts for the check. One is the present Fe distribution of stars in the LMC (Olszewski 1993). It will reflect the SFR history. The other is r which is the contribution of SNe Ia to the enrichment of heavy-elements in the gas. r is defined as

$$r = \frac{\omega_{\mathrm{Ia}} M_{\mathrm{Ia}} N_{\mathrm{Ia}}}{\omega_{\mathrm{Ia}} M_{\mathrm{Ia}} N_{\mathrm{Ia}} + \omega_{\mathrm{II}} M_{\mathrm{II}} N_{\mathrm{II}}} \tag{14}$$

where ω_{Ia} and ω_{II} are mass fractions of heavy-element ejected into the interstellar gas from SNe Ia and SNe II, respectively. ω_{Ia} and ω_{II} are defined as

$$\omega_{\mathrm{Ia}} = \frac{c_{\mathrm{g}} g Z_{\mathrm{g,Fe}}}{c_{\mathrm{s}} s Z_{\mathrm{s,Fe}} + c_{\mathrm{g}} g Z_{\mathrm{g,Fe}} + c_{\mathrm{out}} Z_{\mathrm{out,Fe}}} \tag{15}$$

$$\omega_{\mathrm{II}} = \frac{g Z_{\mathrm{g,O}}}{s Z_{\mathrm{s,O}} + g Z_{\mathrm{g,O}} + m_{\mathrm{out}} Z_{\mathrm{out,O}}} \tag{16}$$

where Z_{g} are the heavy-element abundance in unit mass of the gas. $Z_{\mathrm{s,out}}$ are the heavy-element abundances averaged over the metallicity distribution of stars and outflow, respectively. $m_{\rm out}$ is the total mass that is ejected from the system by the outflow. The factor $c_{\rm s,g,out}$ is introduced to correct the non-negligible SNe II contribution in the iron abundance. These are represented as

$$c_{\rm g,s,out} = 1 - 10^{-[{\rm O/Fe}]_{\rm II}} \frac{(Z_{\rm O}/Z_{\rm Fe})_{\rm g,s,out}}{(Z_{\rm O}/Z_{\rm Fe})_{\odot}}. \tag{17}$$

Using Eq. (10), r is also represented as

$$r = \frac{1}{1 + \frac{P_{1,i}}{P_{2,i}} \frac{M_{\rm II}}{M_{\rm Ia}} \frac{m_{i,\rm Ia}}{m_{i,\rm II}} \frac{\omega_{\rm II}}{\omega_{\rm Ia}} \frac{s(u_{\rm now})}{s(u_{\rm now} - \omega t_{\rm Ia})}}. \tag{18}$$

The i means that ith heavy element is used in estimating r. We emphasize again that r does not depend on i when results of the calculation of supernova nucleosynthesis are used.

We can also infer the value r using the present abundance pattern (Russel & Dopita 1992) and results of supernova nucleosynthesis as follows (Tsujimoto et al. 1995). We define the abundance pattern x_i to be compared with the $x_{i,\rm LMC}$ as

$$x_i(r) = r\frac{m_{i,\rm Ia}}{M_{\rm Ia}} + (1-r)\frac{m_{i,\rm II}}{M_{\rm II}}, \tag{19}$$

and the most probable value of $r = r_p$ is determined by minimizing the following function (Yanagida et al. 1990):

$$g(r) = \sum_{i=1}^{n} [\log x_{i,\rm LMC} - \log x_i(r)]^2/n. \tag{20}$$

Tsujimoto et al. (1995) concluded that $r_p = 0.16$ for the LMC from this fitting (see also Figure 3) using 10 elements (O, Ne, Mg, S, Ar, Ca, Cr, Mn, Fe, and Ni).

3. Results

Values of the input parameters are tabulated in Table 1. Those used in the Pagel model and used in this study (New model) are presented in the table. $P_{1,i}$ and $P_{2,i}$ are written in units of solar abundance of the corresponding element. T_G and $t_{\rm Ia}$ are the age of the LMC and the averaged lifetime of SNe Ia. ω and time are written in units of Gyr^{-1} and Gyr, respectively. $g(t=0)/m(t=T_G)$ is the ratio of the initial mass of gas to the final $(t=T_G)$ total baryon mass. $s(t=0)$ is the initial mass in the form of stars.

EDITOR: PLACE TABLE 1 HERE.

The comparison between the theory and the observations is presented in Figure 1 and Figure 2. In Figure 1, theoretical curves of the Pagel model with observations of the LMC are presented. The age-gas fraction relation, the age-metallicity relation, the [O/Fe] versus [Fe/H] diagram, and the present Fe distribution of long-lived stars are shown, respectively. In Figure 2, theoretical curves with new input parameters are shown. It is noted that Pagel and Tautvaišienė (1998) shifted data points for [O/Fe] upwards by 0.2 dex in their paper. In this study, such a treatment is not done.

EDITOR: PLACE FIGURE 1 HERE.

EDITOR: PLACE FIGURE 2 HERE.

Values of the output parameters are shown in Table 2. $\omega_{\rm Ia}$, $\omega_{\rm II}$, $N_{\rm Ia}/N_{\rm II}$, $\dot{N}_{\rm Ia}/\dot{N}_{\rm II}$, r, x, and A are shown in the table. χ^2 is the value of the chi-square probability function when data sets for the SFR are used. $\overline{|[{\rm O/Fe}]-[{\rm O/Fe}]_{\rm obs}|^2}$ is the mean square of the difference between the observed [O/Fe] and calculated one at the same [Fe/H]. Data points for the [O/Fe] are shifted by 0.2 dex when the value of the $\overline{|[{\rm O/Fe}]-[{\rm O/Fe}]_{\rm obs}|^2}$ for the Pagel model is calculated. As for r, the minimizing function $g(r)$ is shown in Figure 3. $r = 0.16$ (solid vertical line) is the most probable value from the fitting of Eq. (20). $r = 0.12$ and 0.20 are the calculated values by the Pagal and New models, respectively.

EDITOR: PLACE TABLE 2 HERE.

EDITOR: PLACE FIGURE 3 HERE.

Finally, time evolution of the total mass (solid curve), mass of gas (short-dashed curve), and mass of stars (long-dashed curve) concluded by the Pagel and New models are presented in Figure 4. Time is defined as 14 - Age [Gyr].

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4. Discussion

As stated in section 1, chemical evolution model for a galaxy is a tool from which we can infer the history of the galaxy. We determined the values of the input parameters so as to reproduce the observations as one as possible. In this section, we discuss what the New model presented in this study suggests.

As for the ratio $g(t = 0)/m(t = T_G)$, the New model requires relatively high ratio (see Table 1 and Figure 4). This means that we require an initial condition in which star formation is forbidden and only gas exists. What can suppress the star formation at zero metallicity in the LMC? In a simplest situation, a cloud with only thermal support, collapse should occur if the mass exceeds the Jeans (1928) mass,

$$M_J = \left(\frac{\pi k T_K}{\mu m_H G}\right) \rho^{-0.5} = 18 M_\odot T_K^{1.5} n^{-0.5}, \tag{21}$$

where T_K is the kinetic temperature (K), ρ is the mass density (g cm^{-3}), and n is the total particle density (cm^{-3}). So, low temperature and/or high number density are required in order to form a star or, at least, to form a molecular gas cloud. So, it is suggested that the LMC was born in which the temperature is high and/or the particle density is low enough to prevent gas from collapsing and from forming a molecular gas cloud.

We discuss the effect of the outflow. Pagel & Tautvaišienė (1998) introduced an outflow in order to reduce the metallicity of the system. The [O/Fe] ratio is also reduced by the effect of the outflow when a star burst phase is assumed. This is because the material of SNe II is ejected more than that of SNe Ia. However, the Pagel model can not reproduce the SFR history very well (see Figure 1 and the value of the χ^2 probability function in Table 2). On the other hand, the New model can reproduce the present low metallicity and the SFR history at the same time although the New model requires very smaller value for η than the Pagel model. Moreover, the [O/Fe] versus [Fe/H] diagram can be reproduced well without shifting the data points since a low [O/Fe] ratio can be attained by using a high value of A, not by using the effect of the outflow. We could not reproduce the observations well when η is set to be 1.0 like the Pagel model. Although we can not conclude that our solution is an unique one, one has to construct a new parameter set which can reproduce the observations as well as ours if he insists the existence of the outflow in the LMC. Additionally, a steeper IMF slope (Tsujimoto et al. 1995) is not needed in order to attain the low value of the [O/Fe] since a high value of A can realize it.

The ratio $N_{\rm Ia}/N_{\rm II}$ inferred from the New model is very high (=0.48) compared with other models (Tsujimoto et al. 1995; see also Table 2). This is because high ratio of

$P_{2,\mathrm{Fe}}/P_{1,\mathrm{Fe}}$ (i.e. high ratio of A) is assumed in the New model (see Table 1). However, r=0.20 in the New model is close to that inferred from the observations (r=0.16; see Eq. (20)) when the weak dependence of $g(r)$ on r around $r \sim 0.16$ is considered (see Figure 3). That is why we think the high ratio of $N_{\mathrm{Ia}}/N_{\mathrm{II}}$ is not ruled out from the present chemical composition in the LMC. As for the ratio $\dot{N}_{\mathrm{Ia}}/\dot{N}_{\mathrm{II}}$, a higher ratio (= 1.3) is concluded by the New model than the Pagel model. Since such a high ratio, of order 1, is estimated by X-ray observations (Hughes et al. 1995), the New model is thought to be consistent with the observations.

5. Summary

We present a new input parameter set of the Pagel model which reproduces the observations of the LMC very well. The aim of constructing a chemical evolution model is to give some constraints on other theories and numerical calculations. In order to attain such an aim, the chemical evolution model has to explain the observations in the galaxy as many as possible. Although we can not conclude that the New model is an unique solution, we can conclude that no solution which can explain the observations as many as ours has been presented. We hope more observations and further discussions will be presented by many groups in the world in order to understand the system of the large magellanic cloud.

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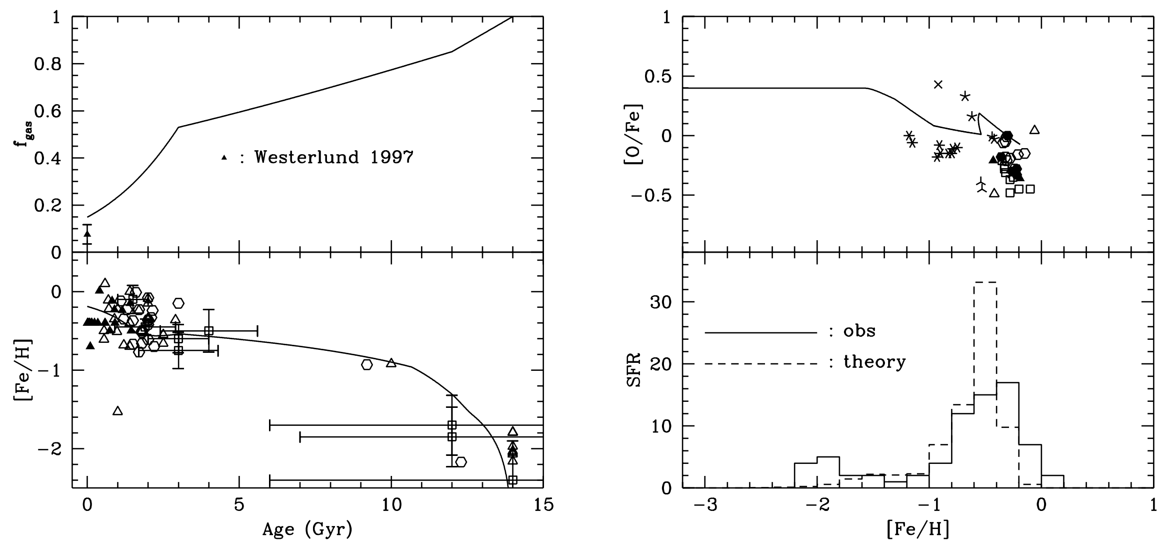

Fig. 1.— Theoretical curves of the Pagel model with observations of the LMC. The upper panel on the left: the age-gas fraction relation. Data point is from Westerlund (1997). The lower panel on the left: the age-metallicity relation. Data sources are as follows: *open triangles*, Olszewski *et al.* (1991); *filled triangles*, Girardi *et al.* (1995); *open hexagons*, Geisler *et al.* (1997); *open squares*, de Freitas Pacheco et al. (1998). The upper panel on the right: the [O/Fe] versus [Fe/H] diagram. Data sources are as follows: *open triangles*, Luck & Lambert (1992); *open squares*, Thévenin (1997); *open hexagons*, Hill, Andriewski & Spite (1995); *filled triangles*, Spite, Barbuy & Spite (1993); *filled hexagons*, Jütter *et al.* (1992); *five − pointed stars*, McWilliam & Williams (1991); *three − pointed stars*, Barbuy, de Freitas Pacheco & Castro (1994); *cross*, Richtler, Spite & Spite (1989); *asterisks*, Nissen & Schuster (1997). The lower panel on the right: the present Fe distribution of long-lived stars. Data source is from Olszewski (1993).

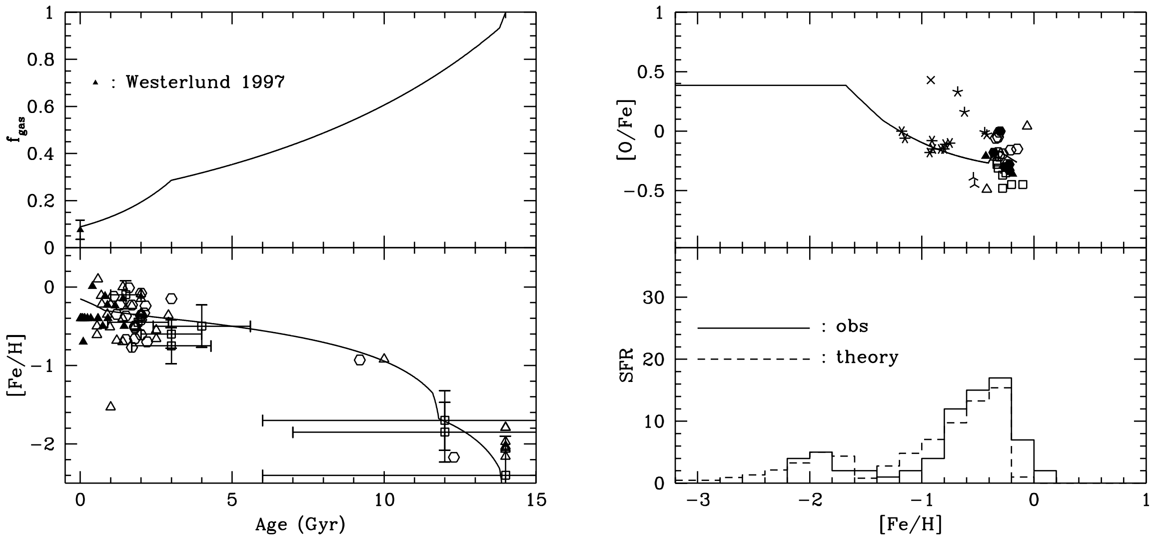

Fig. 2.— Same as Fig.1 but with new input parameters.

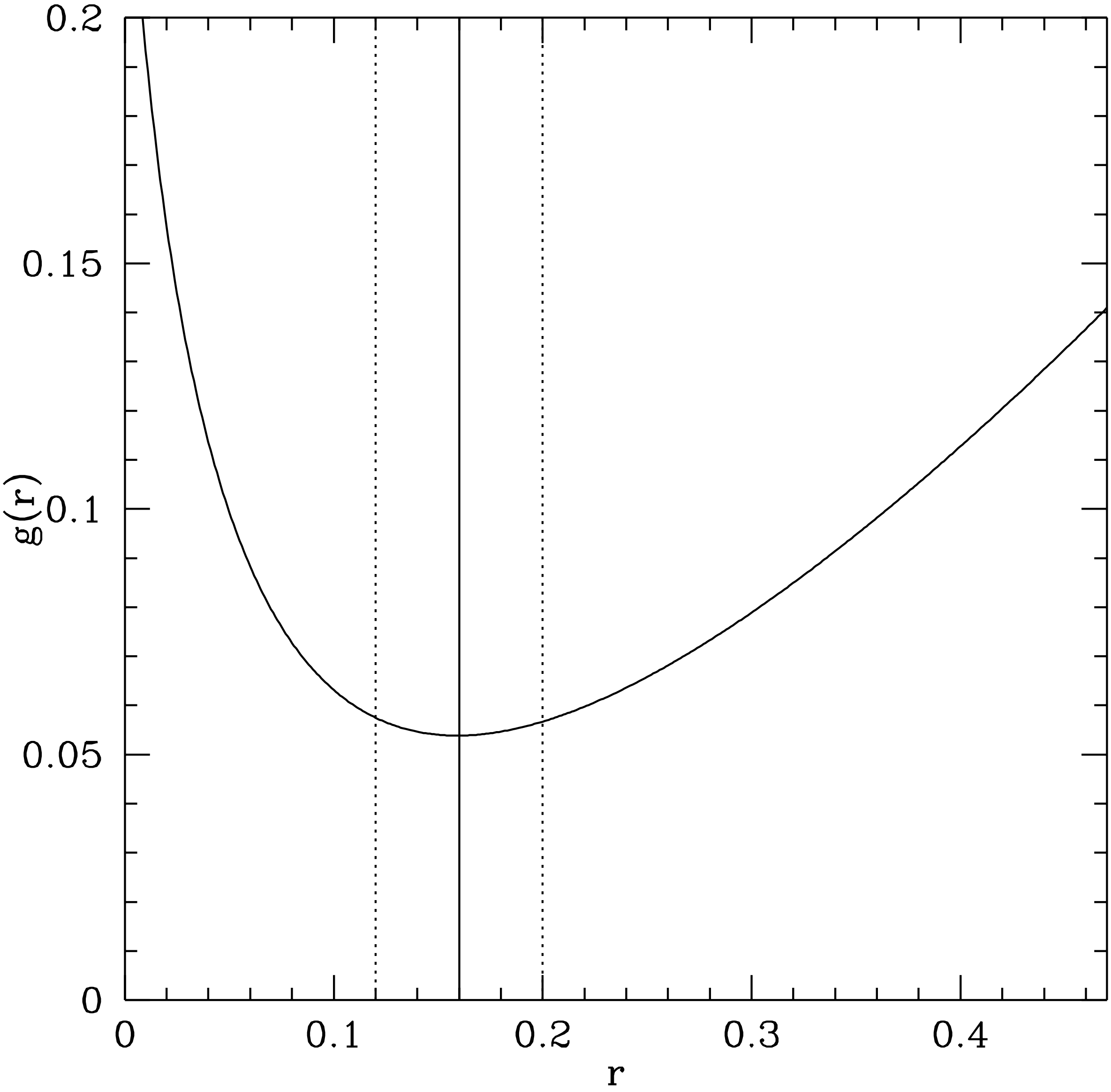

Fig. 3.— The minimizing function $g(r)$ as a function of r. 10 elements (O, Ne, Mg, S, Ar, Ca, Cr, Mn, Fe, and Ni) are used for the fitting. $r = 0.16$ (solid vertical line) is the most probable value. $r = 0.12$ and 0.20 are the calculated values by the Pagal and New models, respectively.

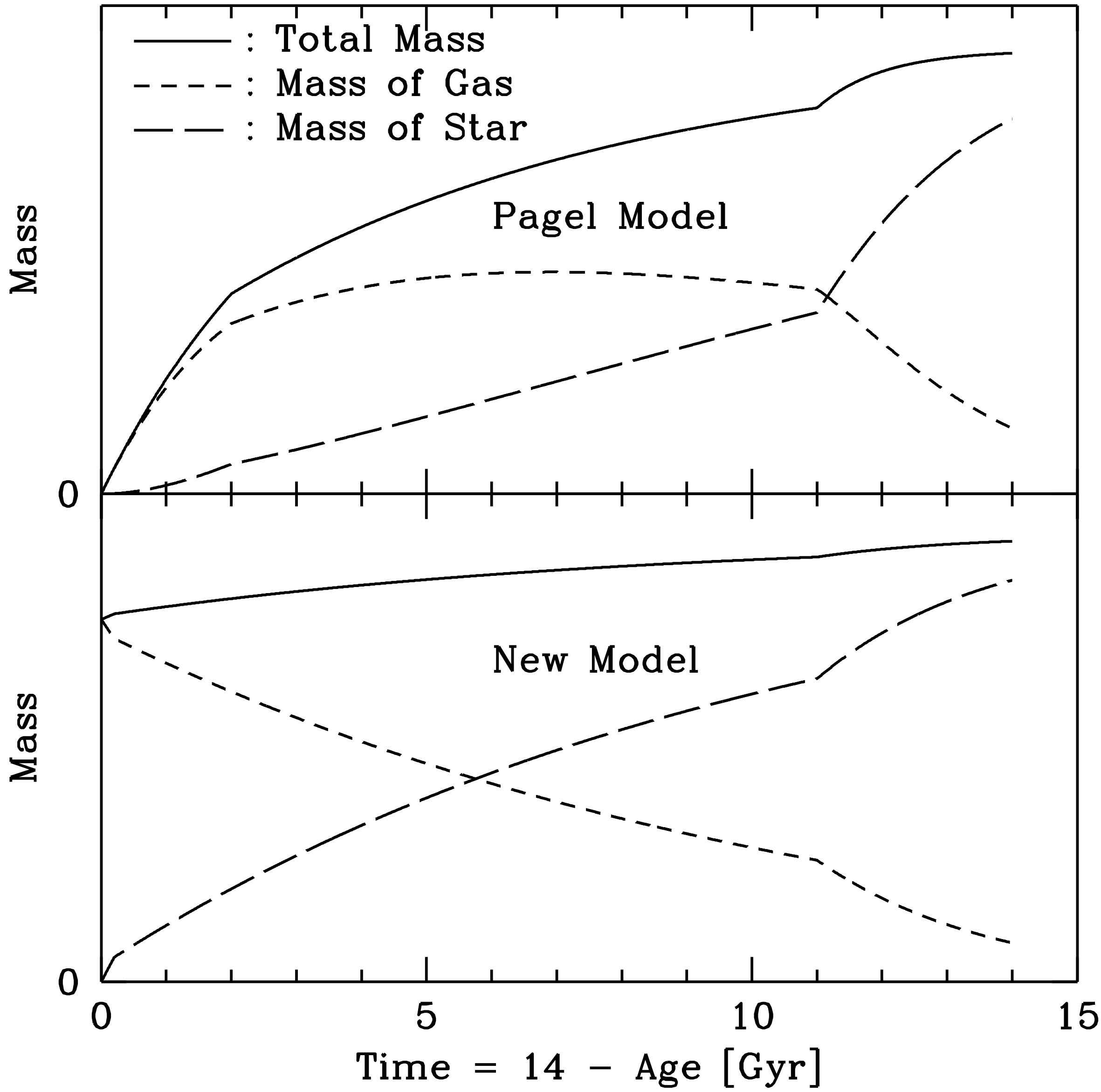

Fig. 4.— Time evolution of the total mass (solid curve), mass of gas (short-dashed curve), and mass of stars (long-dashed curve). Time is defined as 14 - Age [Gyr].

	Pagel Model	New Model
$P_{1,\mathrm{Fe}}/Z_\odot^{\mathrm{Fe}}$	0.28	0.07
$P_{1,\mathrm{O}}/Z_\odot^{\mathrm{O}}$	0.70	0.92
$P_{2,\mathrm{Fe}}/Z_\odot^{\mathrm{Fe}}$	0.42	2.5
T_G (Gyr)	14	14
t_{Ia} (Gyr)	1.33	2.2
η	1.0	0.001
$\omega(t)$	0.15 $(t \leq 2)$	0.35 $(t \leq 0.2)$
	0.08 $(2 \leq t \leq 11)$	0.12 $(0.2 \leq t \leq 11)$
	0.50 $(11 \leq t \leq 14)$	0.45 $(11 \leq t \leq 14)$
$g(t=0)/m(t=T_G)$	0	0.82
$s(t=0)$	0	0

Table 1: Values of the input parameters. Left column: those used in the Pagel model. Right: those used in this study. $P_{1,i}$ and $P_{2,i}$ are written in units of solar abundance of the corresponding element. T_G and t_{Ia} are the age of the LMC and the averaged lifetime of SNe Ia. ω and time are written in units of Gyr^{-1} and Gyr, respectively. $g(t=0)/m(t=T_G)$ is the ratio of the initial mass of gas to the final $(t=T_G)$ total baryon mass. $s(t=0)$ is the initial mass in the form of stars.

	Pagel Model	New Model
$\omega_{\rm Ia}$	0.21	0.25
$\omega_{\rm II}$	0.14	0.21
$N_{\rm Ia}/N_{\rm II}$	0.20	0.48
$\dot{N}_{\rm Ia}/\dot{N}_{\rm II}$	0.42	1.3
r	0.12	0.20
x	1.01	1.06
A	0.075	0.17
χ^2	0.41	0.73
$\overline{\|[{\rm O/Fe}] - [{\rm O/Fe}]_{\rm obs}\|^2}$	0.19	0.19

Table 2: Values of the output parameters. Left column: those derived by the Pagel model. Right: those derived by this study. $\omega_{\rm Ia}$ and $\omega_{\rm II}$ are mass fractions of heavy-element ejected into the interstellar gas from SNe Ia and SNe II, respectively. $N_{\rm Ia}/N_{\rm II}$ and $\dot{N}_{\rm Ia}/\dot{N}_{\rm II}$ are the occurence frequency of SNe Ia relative to SNe II and the ratio of the current supernova rates, respectively. r is the contribution of SNe Ia to the enrichment of heavy-elements in the gas. x is the IMF slope. A is the probability for 3-8$M_\odot$ stars to explode as SNe Ia. χ^2 is the value of the chi-square probability function when data sets for the star formation rate are used. $\overline{|[{\rm O/Fe}] - [{\rm O/Fe}]_{\rm obs}|^2}$ is the mean square of the difference between the observed [O/Fe] and calculated one at the same [Fe/H].